

Baryon Binding Energy in Sakai-Sugimoto Model

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Abstract

The binding energy of baryon has been studied in the dual $AdS_5 \times S^5$ string theory with a black hole interior. Here, we calculate the baryon binding energy in Sakai-Sugimoto model. Also we check the T dependence of the baryon binding energy. We believe that this model represents an accurate description of baryons due to the existence of Chern-Simons coupling with the gauge field on the brane. We obtain an analytical expression for the baryon binding energy. Next we plot the baryon binding energy in terms of radial coordinate. Then by using the binding energy diagram, we determine the stability range for baryon configuration. And also the position and energy of the stable equilibrium point is obtained by the corresponding diagram. Also we plot the baryon binding energy in terms of temperature and estimate a critical temperature in which the baryon would be dissociated.

Keywords: AdS/CFT correspondence; Baryon binding energy; Sakai-Sugimoto model

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1 Introduction

The AdS/CFT correspondence demonstrates a relation between a conformal field theory in d dimension and a gravitational theory in $d + 1$ dimensional anti de-sitter space [1-7]. An example for this correspondence is the relation between type IIB string theory in $AdS_5 \times S^5$ space and $\mathcal{N}=4$ supersymmetric Yang-Mills theory on four dimensional boundary of AdS_5 . Using this correspondence to calculate the complicated problems of QCD is one of the more interesting issues nowadays. For example the dynamics of moving quark in a hot, strongly coupled plasma have been investigated in [8-17]. Also the jet-quenching parameter of quarks is one of the interesting properties of the strongly coupled plasma that there are many calculations to obtain this parameter [17-25]. In Additionally the motion of a quark-antiquark pair have been studied in [26-31].

In the other hand baryons in gauge theory have been studied in $AdS_5 \times S^5$ dual string theory by introducing the baryon vertex [2]. In this picture baryons are corresponded to the configurations which consist of a D_5 -brane wrapped on a S_5 and all external quarks are connected to it due to fundamental strings.

Baryons may also be studied in Sakai-Sugimoto (SS) model [32-35] with $D_4/D_8/\overline{D}_8$ configuration which presents a holographic dual of four dimensional QCD with large N_c and massless flavors. D_4 -brane is placed on a S^1 susy-breaking and the D_8/\overline{D}_8 pairs are transverse to S^1 . The lower bound for the radial coordinate U which is transverse to the D_4 -branes is $U = U_{kk}$ and the radius of S^1 diminishes to zero in this point. The spontaneously symmetry breaking in QCD is indicated as a smooth interpolation of the D_8/\overline{D}_8 pairs in super gravitational background. The SS model suggests that the solution called skyrmion demonstrates a baryon which is considered as a D_4 -brane wrapped on S^4 . This D_4 -brane is the baryon vertex with N_c connected strings. The Chern-Simons coupling leads to the fact that baryon can be treated as a delta function source of the gauge field \mathcal{A}_0 of brane [36].

The phenomenological quantities of baryon at finite temperature are interesting topics, but the calculations are so complicated even in lattice QCD. One can use the dual string theory to analyze most of these concepts. The baryon binding energy, baryon melting temperature and screening length are some of these examples which are investigated using the $AdS_5 \times S^5$ dual string [27,37]. Furthermore some baryon thermodynamical quantities such as the energy density and pressure have been studied in SS model. But the baryon binding energy in SS model have not considered yet and in this paper we plan to analyze it.

In section 2 we review the SS model briefly in which the baryon is considered as a D_4 -brane wrapped on S^4 . In section 3 we use the $U(1)_v$ field introduced by Ref. [32-35] to calculate the energy of baryon configuration in SS model. In section 4 we subtract the dissociated baryon energy and obtain an equation for the baryon binding energy in SS model. Next we plot the energy in terms of radial coordinate and then determine the stability range for baryon configuration in $U_{KK} = 1$ scale. We also obtained the position and energy of the stable equilibrium point by using this diagram. Then we depict the binding energy of baryon versus temperature and estimate the critical T for baryon melting.

2 SS model

In this section we review of Sakai-Sugimoto model with $D_4/D_8/\overline{D}_8$ configuration [32].

The D_4 -brane metric is given by the following equation,

$$ds^2 = \left(\frac{U}{R}\right)^{3/2} (\eta_{\mu\nu} dx^\mu dx^\nu + f(U) d\tau^2) + \left(\frac{R}{U}\right)^{3/2} \left(\frac{dU^2}{f(U)} + U^2 d\Omega_4^2\right),$$

$$e^\phi = g_s \left(\frac{U}{R}\right)^{3/4}, \quad F_4 = dC_3 = \frac{2\pi N_c}{V_4} \epsilon_4, \quad f(U) = 1 - \frac{U_{KK}^3}{U^3}, \quad (1)$$

where D_4 -brane is extended along the x^μ ($\mu = 0, 1, 2, 3$) and τ directions. U ($U \geq U_{KK}$) is the radial coordinate and $d\Omega_4^2$, ϵ_4 and $V_4 = 8\pi^2/3$ are line element, volume form and the volume of S^4 . R and U_{KK} are constant parameters.

Avoiding to have a singularity in $U = U_{KK}$, the τ coordinate should be considered periodic,

$$\tau \sim \tau + \delta\tau, \quad \delta\tau \equiv \frac{4\pi}{3} \frac{R^{3/2}}{U_{KK}^{1/2}}. \quad (2)$$

The R and U_{KK} parameters are defined in terms of l_s and $\lambda(=g_{YM}^2 N_c)$ as follows,

$$R^3 = \frac{1}{2} \frac{\lambda l_s^2}{M_{KK}}, \quad U_{KK} = \frac{2}{9} \lambda M_{KK} l_s^2, \quad g_s = \frac{1}{2\pi} \frac{\lambda}{M_{KK} l_s N_c}, \quad (3)$$

and also the pion decay constant has the following expression,

$$f_\pi^2 = \frac{1}{54\pi^4} (g_{YM}^2 N_c) M_{KK}^2 N_c. \quad (4)$$

according to equation (1) for N_f D_8 -brane placed in D_4 background, equation (1), the action can be written by the follows,

$$\begin{aligned} S_{D8} &= S_{D8}^{DBI} + S_{D8}^{CS}, \\ S_{D8}^{DBI} &= -T_8 \int d^9x \, e^{-\phi} \, \text{tr} \sqrt{-\det(g_{MN} + 2\pi\alpha' F_{MN})}, \\ S_{D8}^{CS} &= \frac{1}{48\pi^3} \int_{D8} C_3 \text{tr} F^3, \end{aligned} \quad (5)$$

where $T_8 = \frac{1}{2\pi^8 l_s^9}$ is the D_8 -brane tension, $F_{MN} = \partial_M A_N - \partial_N A_M - i[A_M, A_N]$, ($M, N = 0, 1, \dots, 8$) is the field strength tensor and A_M is the $U(N_f)$ gauge field on D_8 -brane. The induced metric on D_8 -brane is given,

$$ds^2 = \left(\frac{U}{R}\right)^{3/2} \eta_{\mu\nu} dx^\mu dx^\nu + \left[\left(\frac{U}{R}\right)^{3/2} f(U) (\tau'(U))^2 + \left(\frac{R}{U}\right)^{3/2} \frac{1}{f(U)} \right] dU^2 + \left(\frac{R}{U}\right)^{3/2} U^2 d\Omega_4^2, \quad (6)$$

where $U = U(\tau)$.

Baryon is a D_4 -brane wrapped on S^4 in SS model. In the other hand, it is a soliton in Skyrme model and these two descriptions are related to each other. The topological charge carried by the gauge configuration on D_8 -brane is related to the baryon number charge and the skyrmion constructed on D_8 -brane relates to the wrapping D_4 -brane. The relation between instanton number and D_4 -brane charge is [32],

$$\frac{1}{8\pi^2} \int_B \text{tr} F^2 = n, \quad (7)$$

where $B \simeq R^4$ is the four dimensional space parameterized by (x^1, x^2, x^3, z) .

Inserting the appropriate gauge field in Chern-Simons action, one can write,

$$S_{CS}^{D8} \simeq nN_c \int_R a, \quad (8)$$

where a is the $U(1)_v$ gauge field fluctuations on D_8 -brane.

3 The energy of baryon in SS model

In this section we calculate the energy of baryon configuration in SS model. The CS coupling in SS model leads to the fact that instanton configuration displays a particle with $U(1)_v$ charge nN_c which is equivalent to a particle with baryon number n_B . So we consider the baryon as a delta function source of the gauge field [36]. The baryon action can be regarded as sum of the DBI action and the source action. The DBI action for D_8 -brane in the absence of the source term is written by the following equation,

$$S_{D8} = -\frac{N_f T_8 V_4}{g_s} \int d^4x dU U^4 \left[f (\tau')^2 + \left(\frac{R}{U} \right)^3 \left(f^{-1} - (2\pi\alpha' \mathcal{A}'_0)^2 \right) \right]^{\frac{1}{2}}, \quad (9)$$

where $\mathcal{A}'_0 = \frac{d\mathcal{A}_0}{dU}$ and the CS term vanishes. From the equation of motion for $\tau(U)$ only the $\tau' = 0$ case is considered [32]. It means that the existence of \mathcal{A}_0 does not change the D_8 -brane configurations in τ coordinate. And it corresponds to $\tau = \frac{\delta\tau}{4}$ which is the maximum of asymptotic separation between D_8 and $\overline{D_8}$.

In order to express our results according to the SS model we choose z instead of U as,

$$U \equiv (U_{KK}^3 + U_{KK} z^2)^{1/3}, \quad (10)$$

and then use the following dimensionless parameters,

$$Z \equiv \frac{z}{U_{KK}}, \quad K(U) \equiv 1 + Z^2 = \left(\frac{U}{U_{KK}} \right)^3. \quad (11)$$

Then, one can rewrite the action (9) in the following form,

$$S_{D8} = -a \int d^4x \int dZ K^{2/3} \sqrt{1 - bK^{1/3}(\partial_Z \mathcal{A}_0)^2}, \quad (12)$$

where

$$a \equiv \frac{N_c N_f l_s^3 M_{\text{KK}}^4}{3^9 \pi^5} , \quad b \equiv \frac{3^6 \pi^2}{4 l_s^2 M_{\text{KK}}^2} . \quad (13)$$

In the other hand, the source action has the following form [36],

$$S_{\text{source}} = N_c n_B \int d^4 x \int dZ \delta(Z) \mathcal{A}_0(Z). \quad (14)$$

where $N_c n_b = n_q$ is the quark density.

Now by using the equations (12) and (14), we write the baryon action as follows,

$$\begin{aligned} S_{\text{Baryon}} = & - a \int d^4 x \int dZ K^{2/3} \sqrt{1 - b K^{1/3} (\partial_Z \mathcal{A}_0)^2} \\ & + N_c n_B \int d^4 x \int dZ \delta(Z) \mathcal{A}_0(Z). \end{aligned} \quad (15)$$

At first, we should solve the equation of motion for the gauge field to reach the baryon hamiltonian,

$$\frac{d}{dZ} \frac{\partial \mathcal{L}}{\partial (\partial_Z \mathcal{A}_0)} = n_q \delta(Z) , \quad (16)$$

By the definition $D = \frac{\partial \mathcal{L}}{\partial (\partial_Z \mathcal{A}_0)}$ and integrating over z , the equation of motion takes the following form,

$$D = \frac{1}{2} n_q \text{sgn}(Z) . \quad (17)$$

In that case the equation (18) helps us to obtain the corresponding baryon action and energy. We utilize the definition of D to eliminate $\partial_Z \mathcal{A}_0$ as following,

$$(\partial_Z \mathcal{A}_0)^2 = \frac{D^2}{a^2 b^2 K^2 + b D^2 K^{1/3}} . \quad (18)$$

Inserting this equation into the baryon action (16) yields to,

$$\begin{aligned} S_{\text{Baryon}} = & - 2a^2 b \int d^4 x \int dZ K^{5/3} (4a^2 b^2 K^2 + n_q^2 b K^{1/3})^{-1/2} \\ & + n_q \int d^4 x \int dZ \delta(Z) \mathcal{A}_0(Z), \end{aligned} \quad (19)$$

which is independent of $\partial_Z \mathcal{A}_0$.

Then to obtain the baryon energy we should transform the original lagrangian to eliminate the gauge field in favor of D as follows,

$$\mathcal{L}_{\text{Baryon}} \rightarrow n_q \delta(Z) \mathcal{A}_0(Z) - \mathcal{L}_{\text{Baryon}}. \quad (20)$$

After this transformation, the baryon lagrangian will be following,

$$\mathcal{L}_{\text{Baryon}} = 2a^2 b K^{5/3} (4a^2 b^2 K^2 + n_q^2 b K^{1/3})^{-1/2}. \quad (21)$$

Substituting this equation into the baryon action (19) we find the energy of baryon configuration as following,

$$E_{\text{Baryon}} = 2a^2 b V_3 \int dZ K^{5/3} (4a^2 b^2 K^2 + n_q^2 b K^{1/3})^{-1/2}, \quad (22)$$

where V_3 is the spatial integral. Here we attain an equation for the baryon energy assuming the baryon as a delta function in terms of the SS model parameters.

4 Baryon binding energy

In this section we obtain the baryon binding energy with a good approximation. For this purpose we should subtract the energy of dissociated baryon from the total energy of baryon configuration (equation (21)).

By using the following relation the energy of dissociated baryon is considered as the mass of N_c deconfined quarks at the black hole horizon,

$$E_{diss} = \frac{N_c}{2\pi\alpha'} \int dU. \quad (23)$$

where we assumed $\phi = 0$ for the dilaton.

Then we have applied the equations (10) and (11) and rewrite the equation (24) in terms of new dimensionless variable Z as follows,

$$E_{diss} = c \int dZ Z K^{-2/3}, \quad (24)$$

where

$$c = \frac{N_c U_{KK}}{3\pi\alpha'}. \quad (25)$$

Subtracting this equation from the baryon energy (equation (22)), one can obtain the following equation for the baryon binding energy,

$$E_I = 2a^2bV_3 \int dZ K^{5/3} (4a^2b^2K^2 + n_q^2bK^{1/3})^{-1/2} - c \int dZ Z K^{-2/3}. \quad (26)$$

The first integrate can not be solved analytically but we have to consider the following condition which is obtained by numerical values for the parameters,

$$n_B < \frac{N_f \lambda^2 M_{KK}^3}{3^6 \pi^4}. \quad (27)$$

which implies that $n_q < 2ab^{1/2}$ and simplifies the integrand. Thus the baryon binding energy is approximated up to the second order of the power expansion,

$$E_I = aV_3 \int dZ K^{2/3} \left\{ 1 - \frac{1}{2} \frac{n_q^2}{2a^2bK^{5/3}} + \dots \right\} - c \int dZ Z K^{-2/3}, \quad (28)$$

which has analytical solution in terms of the hypergeometric functions as follows,

$$\begin{aligned} E_I &= aV_3 Z F\left(\left[\frac{-2}{3}, \frac{1}{2}\right], \left[\frac{3}{2}\right], -Z^2\right) \\ &- \frac{1}{2}c Z^2 F\left(\left[\frac{2}{3}, 1\right], [2], -Z^2\right) - \frac{1}{8} \frac{V_3 n_q^2}{ab} \tan^{-1}(Z). \end{aligned} \quad (29)$$

This is the baryon binding energy in terms of the dimensionless parameter Z introduced in SS model.

Finally we change Z into U , the radial coordinate in SS model, and plot the baryon binding energy in terms of this coordinate. Then, we use this plot to determine the range of U in which the baryon is stable in SS model. We also appraise the position and energy of the stable equilibrium point. The equation (27) is applied for baryon density and the numerical value of λ is obtained from equation (4) with $f_\pi = 0.093 \text{ GeV}$ for the experimental value of the pion decay constant. Also we choose $N_f = 2$ and $N_c = 3$ values and insert

these values with $M_{kk} = 0.950 \text{ GeV}$ in equation (29). Then we plot the baryon binding energy with respect to the U coordinate in $U_{kk} = 1$ scale (figure 1-a). As U increases, the binding energy of baryon configuration gets smaller and at $U = U_b$ we have an stable equilibrium point with the minimum energy of $E_I = -2.36 \text{ GeV}$. At $U = U_m$ the binding energy is zero and for $U > U_m$ the baryon would be dissociated. So we obtain an stable range for the baryon configuration.

Furthermore, in equation (29) we use the relation between the horizon coordinate U_{KK} and the temperature to depict the baryon binding energy in terms of T at $U = U_m$ (figure 1-b). As T increases, the baryon binding energy becomes larger and for $T > T_c$ we have no stable configuration. Note that we obtained a similar behavior for the binding energy versus T compared to Ref.[37] with the $AdS_5 \times S^5$ configuration.

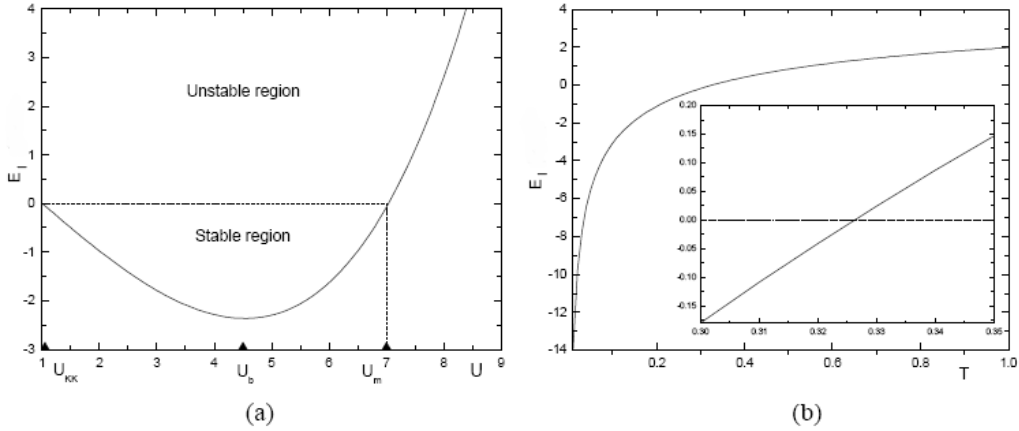


Figure 1: a) The baryon binding energy vs. U coordinate in SS model. The baryon is stable in $U_{kk} < U < U_m$ range and $U = U_b$ is the stable equilibrium point. b) The baryon binding energy vs. T . T_c is the temperature in which the binding energy becomes zero and for $T > T_c$ no stable configuration exists.

5 Conclusion

We calculated the binding energy of baryon in the gauge/gravity dual description with a $D_4/D_8/\overline{D}_8$ introduced in SS model. Here we considered the baryon action as the sum of the DBI action and a delta function source of the gauge field as in [36]. We obtained the total energy of baryon and the energy of N_c fundamental quarks in section 3. Then in order to obtain the baryon binding energy, we subtracted the energy of dissociated baryon from the total energy of baryon. Finally we depicted the baryon binding energy versus the radial coordinate and determined the stability range for baryon configuration by using this diagram. Also we plotted the baryon binding energy versus the temperature. Then the critical temperature T_c can be realized clearly.

According to the binding energy graph we can easily find that the baryon binding energy is zero at $U = U_{kk}$ which is the lower bound for U coordinate in SS model where the radius of S^1 diminishes to zero and no stable baryon configuration exists. As U increases, the binding energy of baryon configuration gets smaller and at $U = U_b$ we have an stable equilibrium point. For $U > U_b$ the energy increases and at $U = U_m$ the binding energy vanishes again. It reveals the fact that for $U > U_m$ there is no stable baryon configuration and the baryon would be dissociated. Furthermore we obtained a similar behavior for the binding energy versus T compared to Ref.[37] which proposes an $AdS_5 \times S^5$ configuration.

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